EXPERIMENTAL INTRODUCTION TO EXTRA DIMENSIONS [1]

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abstract.

A short review of phenomenological and experimental aspects of extra spatial dimensions at colliders is presented.

1 Introduction

How old is the idea of extra spatial dimensions ? The answer to this question appears to deeply vary wether you ask, among others, religion [1], literature, philosophy, mathematics or physics. Focusing on physics, the first serious discussions of extra spatial dimensions seem to bring us at the beginning of last century with the work of Nordström [2], Kaluza [3], Klein [4] and then Einstein and Bergmann [5] who already tackled the problem of unifying the electromagnetic interaction with the gravitational interaction.

Although supergravity theories formulated up to 11 spacetime dimensions and superstring theories in 10 spacetime dimensions (10d) were known since the 70' and 80' [6], still pursuing the goal of unifying all the known interactions, the idea of extra spatial dimensions received recently a new impulse. Actually, efforts of undertanding spontaneous supersymmetry breaking by compactification in the context of string theories lead already to the

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possibility of having extra spatial dimensions at the TeV scale [8]. Afterwards, a better understanding of the role of branes in superstrings theories and the relation between the five 10d superstrings theories in terms of duality symetries, leading to the existence of a M-theory, having the 11d supergravity theory as its low energy limit, has been exploited up to the striking statement that the fundamental string scale is viewed as an arbitrary scale which can be, formally, as low as the TeV scale [7] thus leading to the possibility of having extra spatial dimensions at this scale. Futhermore, the proposal of having the standard model (SM) fields of particle physics confined on a 4d subspace (brane) living in a $(4+n)$d space with n compact extra spatial dimensions where the gravitational interaction lives [9] and arguing a TeV scale as the fundamental scale for the gravitational interaction in this $(4+n)$d space lead to the possibility of having large compact extra spatial dimensions i.e. of the mm size as well as an automatic mean of solving the hierarchy problem of the SM. It is quite remarkable that this last proposal, often referred as the ADD approach, can be embedded within the context of string theories [10]. Even more recently, the set-up with two 4d branes (one of which containing the SM fields) living in a 5d space with an anti-De-Sitter (AdS) geometry provides an additional scenario and more impulse to the idea of extra spatial dimensions. This approach is often referred as the model with warped extra spatial dimension or the Randall-Sundrum (RS) model [18].

We don't experience more than 3 spatial dimensions in our everyday life. This means that extra spatial dimensions wether compact (i.e. up to 6 compact extra space dimensions within superstring theories or 7 in M-theory) or warped (i.e. 1 within the Randall-Sundrum approach) are hidden because their sizes are still smaller than what can be resolved by our past and past/present experimental apparatus. More performing experimental apparatus for new measurements of the gravitational law between test bodies being separated by distances below the O(1 mm) scale where compact extra spatial dimensions are supposed to manifest are now being designed and/or taking data. This field of activities is described elsewhere in these proceedings, see [19] and [20].

At colliders, extra spatial dimensions, manifest themselves through the production of Kaluza-Klein states. In the presence of an compact extra spatial dimension y, a field $\phi(x_\mu, y)$ of mass m_o is periodic over y and can be Fourier developped:

$$\phi(x_\mu, y) = \sum_{k=-\infty}^{+\infty} e^{\frac{iky}{R}} \phi^{(k)}(x_\mu) \tag{1}$$

where R stands for the radius of the compact extra spatial dimension. The 4d restriction $\phi^{(k)}(x_\mu)$ of the field $\phi(x_\mu, y)$ are the Kaluza Klein states (or modes or excitations) of $\phi(x_\mu, y)$. The number Kaluza Klein states is infinite and Kaluza Klein states have masses given by $m_k^2 = m_o^2 + (k^2/R^2)$. In the following, the production and experimental signature of the various type of Kaluza-Klein states at colliders are discussed. The search for these signatures and present experimental results are discussed by E. Perez [21] in these proceedings. The search for extra-dimensions at future colliders are discussed by K. Benakli [22] also in these proceedings.

2 Compact extra spatial dimensions in flat geometry

2.1 TeV Gravity alone

In the ADD approach mentioned above, only the gravitational interaction lives in the complete space (bulk) made of the 4d subspace where the SM fields lives and of n compact extra spatial dimensions (CESD). In this approach the known Planck mass scale in 4d can be related to the fundamental scale in the bulk i.e. $M_{Pl(4+n)} \equiv M_D$, by:

$$M^2_{Pl(4)} = M^{n+2}_{Pl(4+n)} R^n \tag{2}$$

where R is the radius of the CESD. The magnitude of the 4d Planck mass scale is then understood as coming from a O(1TeV) fundamental scale M_D in the bulk and large volumes from large CESD i.e. $R \sim 1$ mm for $n = 2$ [2]. A O(1TeV) fundamental scale automatically suppresses the hierarchy problem of the SM.

The graviton is the particle associated to the gravitational interaction in the bulk. This graviton is then a bulk graviton. The 4d SM fields couple to the 4d restriction of the bulk graviton namely its Kaluza-Klein (KK) states. This coupling is suppressed by the 4d Planck mass. However the smallness of this coupling is compensated by the mass degeneracy of KK-graviton states. The mass interval between 2 KK-graviton states is given by $\Delta m \sim (\frac{M_D}{TeV})^{\frac{n+2}{2}} 10^{\frac{12n-31}{n}}$ which gives $\Delta m \sim 3 10^{-4} eV$ for $n = 2$ and $M_D =$1 TeV. This compensation allows for sizeable cross-sections at colliders for processes involving the production of KK-graviton states [11].

[2] The above relation between the 4d Planck scale and the fundamental scale in the bulk can be derived by using the Gauss law. It can also be derived within the context of type I/I' string theory

At colliders, the direct production of KK-graviton states will depend mainly on the center-of-mass energies E of the particles involved in the collision, the number n of CESD and the scale M_D namely $\sigma \sim E^n/M_D^{n+2}$. The KK-graviton states produced are only 4d resctrictions of bulk gravitons so that 4d KK-gravitons disappear in the bulk (from our 4d point of view). In consequence, the direct production of KK-graviton states at colliders gives rise to events with a large missing energy component ($\not{E}$) in their signatures in a detector. For example, at e^+e^- colliders, KK-graviton states can be produced in association with a γ or a Z boson leading $\gamma\ \not{E}$ or $Z\ \not{E}$ signatures. At pp or $p\bar{p}$ colliders the signatures for the production of KK-graviton states are jet $\not{E}$, $\gamma\ \not{E}$ and $Z\ \not{E}$. The detection and measurement of such signatures allow for direct measurements of the number of CESD and the scale M_D [11]. Di-fermions or di-bosons production at e^+e^-, pp, $p\bar{p}$ or ep colliders are also affected by processes involving KK-graviton states. These indirect effects are signed by deviations in differential cross-sections and asymmetries measurements with respect to the expectation from pure SM processes [11]. However, for $n \geq 2$, the cross-section of these indirect processes involving KK-graviton states are divergent. At the level of field theory calculations, a cut-off is usually imposed in order to remove theses divergencies. This cut-off is unfortunately related to the fundamental scale M_D up to an arbitrary parameter usually and reasonably assumed to be of order 1. It is worth mentioning that at the level of string theories calculations, in particular in the context of type I string theory, the above divergencies can be regularized [23].

Most of the searches for direct or indirect effects from large CESD at past and past/present colliders have been performed within this ADD approach of TeV Gravity alone. The results of these searches are discussed elsewhere in these proceedings [21]. The discussion of these signatures at future colliders are also discussed elsewhere in these proceedings [22].

One of the most stringent constraint on M_D and/or the radius R of CESD comes from the observation that KK-graviton states emission would have affected the energy release of supernova SN1987A [24]. This observation turns into the following constraints $M_D > 50 - 130$ TeV and $R < 3\,10^{-4}$ mm for $n = 2$. However, in the derivation of these contraints, it is usually assumed that all large CESD radii are of the same order of magnitude leading to an isotropy-like assumption. This requirement seems still to be justified [25].

Gravity in higher dimensional spaces does not only imply the existence of KK-graviton states in 4 dimensions but also spin 1 and spin 0 new KK-states which can interact with SM fields. The spin 0 states i.e. the graviscalars, couple to the SM fields via the trace of the energy-momentum tensor. The direct production of KK-graviscalars is suppressed relative to KK-graviton [30] due either to the anomaly loop factor (trace anomaly) or to additional power of m_Z^2/E^2. However, in the present field theory approach, it is possible to consider a mixing between KK-graviscalars and the Higgs boson which can lead to a sizeable invisible Higgs branching fraction. This invisible Higgs branching fraction can even reach values near 1, as seen in Fig. 1 from [30], depending of the conformal coupling responsible of the graviscalars-Higgs boson mixing thus having a great impact on Higgs boson search at the Tevatron and LHC.

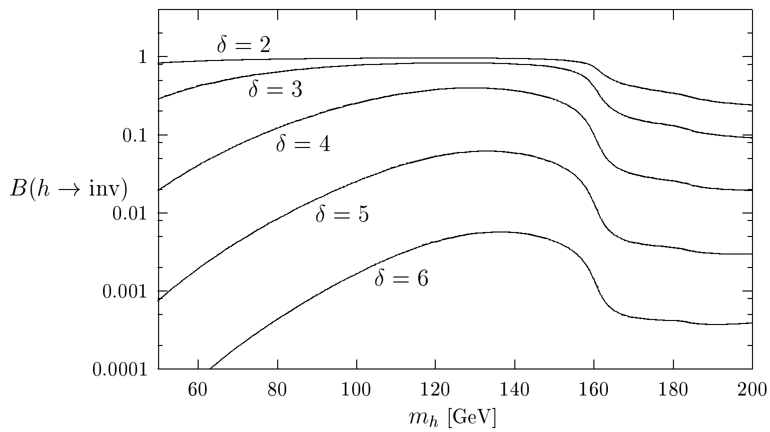

Figure 1: The Higgs boson invisible branching fractions as a function of its mass for $M_D = 2$ TeV and a conformal coupling (see text) equal to 1.

Before ending this section it is worth emphasizing that the ADD approach can be embedded within string theories and in particular the type I string theory. More generally, when dealing with a quantum theory of gravitation, one has always to keep in mind that string theories are presently the best approaches for such a theory. The spectrum of string oscillations states does not only allow for zero mass states identified with the known particles but also for massive states whose masses are of the order of the string scale. If the string scale is lowered down to a scale of O(1) TeV then these massive states arise with the same mass and thus may contribute to observable effects at colliders. These stringy effects can even dominate those coming from pure KK-graviton states since their contribution to 4-points amplitudes appear as form factors containing correction of order $g_s(E/M_s)^4$ where $g_s \sim 1/25$ and M_s are the string coupling and the string scale respectively while KK-graviton effects have $g_s^2(E/M_s)^4$ factors i.e. a g_s^2 dependence [23].

2.2 Kaluza Klein gauge bosons

The embedding of the ADD approach within type I string theory and its brane point of view allows to enrich the spectrum of KK states as, in this framework, one is not only left with KK-graviton states coming from graviton in the usual perpendicular CESD but also to the possiblity of having KK-gauge bosons coming from the gauge bosons of the SM living in so-called parallel CESD [12]. The possibility of producing KK-gauge bosons at colliders has been actually already discussed in [13]. It has also been realized that in the context of compactified type IIB string theory KK-excitations states having gauge interactions can arise while the gravity becomes strong at scales kept at $O(10^9)$ TeV [14].

The effects of KK-gauge bosons can be either seen by their effects on electroweak observables in precision measurements or in particles production at colliders. The analysis of the effects of KK-gauge bosons on electroweak (EW) observables often requires some generic assumptions such as, 1) the non influence of gravitational effects, 2) only one extra dimension usually compactified on the S^1/Z_2 orbifold, where the Z_2 symmetry appears to be useful to introduce fermions chirality on the 4d branes localized at the fixed points of the orbifold, 3) the choice of the reference model i.e. SM, MSSM or even NMSSM and finally 4) the localization of the fields i.e. for the SM, the fermions on the 4d branes localized on the fixed point of the above orbifold, the gauge fields in the 5d bulk and the Higgs field either in the brane or in the bulk. In addition, the effective 5d gauge coupling $\hat{g}$ is often given in terms of the 4d gauge coupling g i.e. $\hat{g}^2 \sim g^2 R$ where $R \sim 1/M_c$ is the radius of the parallel CESD and M_c the scale of this parallel CESD. This effective gauge coupling in 5d has been shown to be finite while for more than one parallel CESD the effective gauge coupling is divergent. However, in the context of string theories, the brane configuration has to be taken into account in order to define the gauge coupling which can then be regularized. The results in terms of constraints on R or M_c from EW precision measurement is given elsewhere in these proceedings [21]. In order to fix the order of magnitude on M_c, a global fit from the EW precision measurements from the LEP experiments allows to derive $M_c > 3.5$ TeV [15].

At this stage, it is important to note that grand unification at intermediate mass scales through extra dimensions has been discussed in [16] as early as the ADD scenario. This analysis involves the MSSM as the reference model, and it has been shown that the gauge couplings unification might be brought down to low energy scales due to the presence of KK-states, including KK-gauge bosons. These KK-states are responsible for a power law contribution to the running of the gauge couplings.

At colliders, KK-gauge bosons can be directly produced as resonances if their masses are kinematically accessible. The KK-gauge bosons decay into pairs of leptons or into pairs of quarks giving rise to 2 hadronic jets. The masses of these KK-gauge bosons are then given by the 2-leptons invariant mass (or transverse mass) or by the 2-jets invariant mass. If their masses are not kinematically accessible, the effects of KK-gauge bosons is signed by deviations in differential cross-sections and asymmetries measurements with respect to the expectation from pure SM processes. Moreover, the clean environment of leptonic colliders allows for a measurement of the KK-gauge bosons coupling to fermions thus allowing for a possible model disentangling [17]. The perspectives for direct or indirect signals for KK-gauge bosons at future colliders are given elsewhere in these proceedings [22].

3 Warped extra spatial dimension

Another approach for extra spatial dimensions has been proposed in [18]. In this scenario two 4d branes with tensions V and V' are situated at $y = 0$ and $y = \pi r_c$ of a 5d bulk with cosmological constant λ where gravitation lives. With this setup, the metric $ds^2 = e^{-2k|y|}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2$, where k is a scale factor of the order of the 4d Planck scale, is a solution of Einstein equations provided $V = V' = 24\, M_5^3 k$ and $\Lambda = -24\, M_5^3 k^2$ i.e. a negative cosmological constant in the bulk thus corresponding to an Anti-De Sitter (AdS) geometry. The factor $e^{-2k|y|}$ which is in front on the usual 4d part of the metric and which depends on the 5th dimension is often referred as the warp factor.

One of the interesting consequence of this approach comes from the observation that a fundamental mass scale on the brane at $y = 0$ is red-shifted by this warp factor on the other brane at $y = \pi r_c$. Thus, with $kr_c \sim 12$ a O(1) TeV mass scale can be produced from the Planck mass scale which can provide a hint for the understanding of the hierarchy between the EW scale and the 4d Planck mass scale.

In constrast to the ADD approach, the 4d Planck mass is now given by:

$$\bar{M}_{Pl}^2 = \frac{M_5^3}{k}[1 - e^{-2kr_c\pi}] \tag{3}$$

which remains well defined even for $r_c \to \infty$. Furthermore, also in constrast to the ADD approach, the KK expansion of the graviton is now given in terms of linear combinations of Bessel functions and thus the masses of KK-graviton, expected to be $O(1)$ TeV, are no longer equally spaced but are then given by $m_n = x_n k e^{-k\pi r_c}$ where x_n are roots of Bessel functions. The coupling of the KK-graviton 0-mode state to the fields of the SM is suppressed by the 4d Planck mass. Nevertheless, the non-zero modes can be directly produced at colliders if kinematically accessible since their coupling to the SM fields is only suppressed by the 4d Planck mass red-shifted by the warp factor i.e. $1/(e^{-k\pi r_c} M_{Pl})$. The phenomenology of warped extra dimension (WED) usually depends on 2 parameters $e^{-k\pi r_c}$ and k/M_{Pl}.

At colliders such as the Tevatron or the LHC, KK-graviton states from WED can be produced as resonances. These resonances then decay predominantly into two hadronic jets [26] and this channel channel dominates the other channels i.e. W^+W^-, ZZ, l^+l^-, $t\bar{t}$ and hh. Although not the dominant channel, the two leptons channel l^+l^- allows for a clean signature of the KK-graviton from WED at hadronic colliders such as the LHC. Then the measurement of the two leptons invariant mass allows to measure the mass of this KK-graviton and the measurement of the (polar) angular differential cross-section allows to establish its spin. Fig. 2 from [26] shows the allowed region for the 1st KK-graviton state of mass m_1 and with $\Lambda_\pi = \bar{M}_{Pl} e^{-kr_c\pi}$. The oblique parameters lines come from a global fit to the S and T oblique parameters [27].

3.1 Radion phenomenology

In this WED approach, r_c is associated with the vacuum expectation value of a massless 4d scalar field which is known as the modulus field or the radion. The presence of a scalar field in the bulk with interaction terms localized on the branes, allows to stabilize the value of r_c [28]. In order to have $kr_c \sim 12$ as argued in the previous section, the radion, after stabilization, should be lighter than the KK-graviton states from WED and is then likely to be the first state accessible at colliders. The radion couples to the SM fields via the trace of the energy-momentum tensor with strength given by $1/\Lambda_\phi$ with $\Lambda_\phi = (\sqrt{24M_5^3/k})e^{-kr_c\pi}$. Fig. 3 from [29] shows the radion production cross section via gluon fusion at the Tevatron ($\sqrt{s} = 2$ TeV) and the LHC

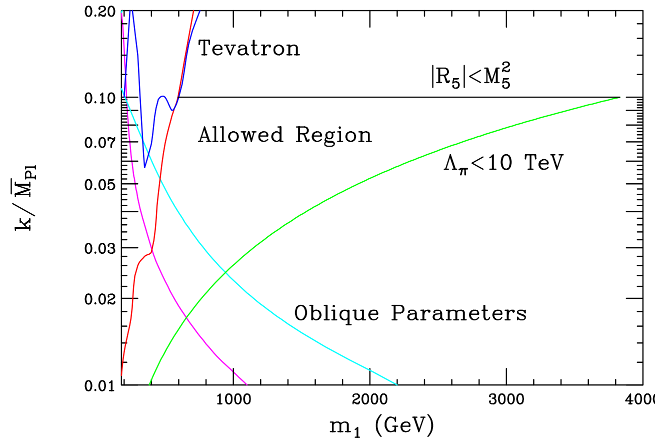

Figure 2: Allowed region in the $k/\bar{M}_{Pl}$ and m_1 plane where m_1 is the mass of the 1st KK-graviton and $\Lambda_\pi = \bar{M}_{Pl} e^{-kr_c\pi}$. The oblique parameters lines come from a global fit to the S and T oblique parameters .

($\sqrt{s} = 14$ TeV) compared to the Higgs production cross sections. The radion decays predominantly into W^+W^-, ZZ, hh, $t\bar{t}$ if kinematically allowed, otherwise it decays mainly into a pair of gluons and, to a less extent, into $b\bar{b}$. The radion phenomenology is very similar to the SM Higgs boson except that its coupling to two gluons (production and decay) is enhanced by the trace anomaly. However, it is possible to consider a possible mixing between the Higgs boson and the radion [30] giving rise to two new eigenstates. These new eigenstates can have quite different branching fractions i.e. up to factors of order 50, in particular for the decays into W^+W^- and ZZ depending on the conformal coupling which is responsible of this Higgs-radion mixing.

4 Conclusions

The recent new impulse given to the idea of extra spatial dimensions have led to a rich spectrum of approaches either in the flat geometry stream (ADD) and its embedding within stringy scenarios or in the warped geometry (RS) stream. The phenomenology connected to these various approaches is in its

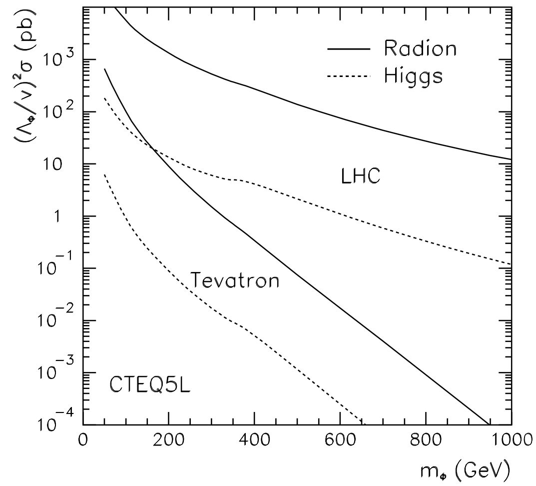

Figure 3: The radion production cross section via gluon fusion at the Tevatron ($\sqrt{s} = 2$ TeV) and the LHC ($\sqrt{s} = 14$ TeV) with a scale factor (Λ_ϕ/v where v is the Higgs boson v.e.v and Λ_ϕ is defined in the text) compared to the Higgs boson production cross sections (dashed lines).

infancy and is still developping. These phenomenological developpements are carried out in connection with more fundamental/theoretical works in the hope to extract more motivated models. Many tests can already be performed at present and future experiments including sub-millimeter gravity measurement and experiments at present and future colliders. A short review of phenomenological and experimental aspects of extra spatial dimensions at colliders has been presented. However many topics not covered here are highly worth to be looked at. This includes topics such as fermions masses within branes worlds, phenomenology from the supersymmetrization of extra dimension models, EW and supersymmetry breaking within brane worlds not to speak about the impact of extra dimensions on astrophysics and cosmology.

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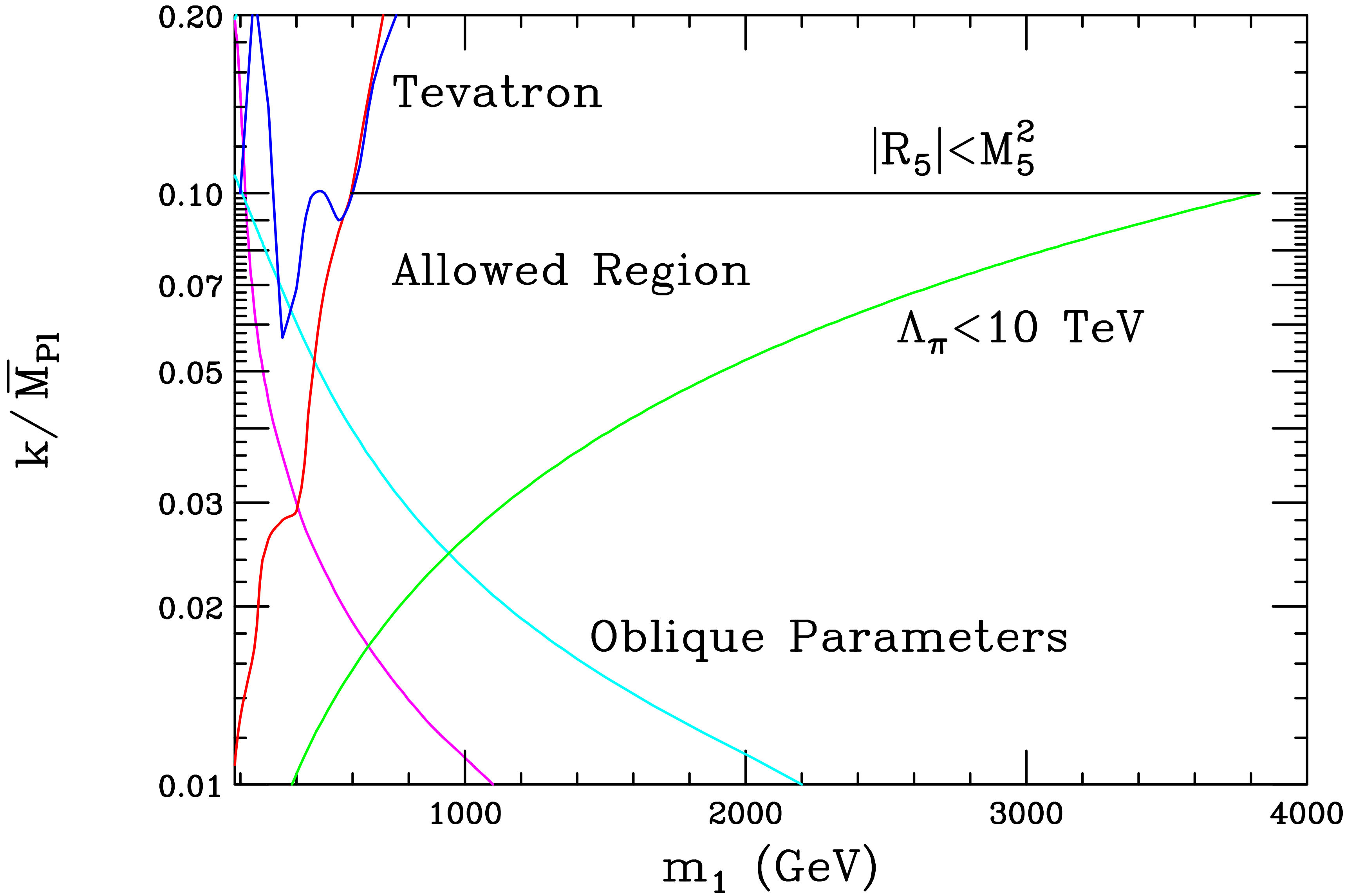

Tevatron
$|R_5|<M_5^2$
Allowed Region
$\Lambda_\pi<10$ TeV
Oblique Parameters
0.20
0.10
0.07
0.05
0.03
0.02
0.01
1000
2000
3000
4000
$k/\overline{M}_{Pl}$
m_1 (GeV)